Optimizing the HINS Hydrogen Ion Source

By

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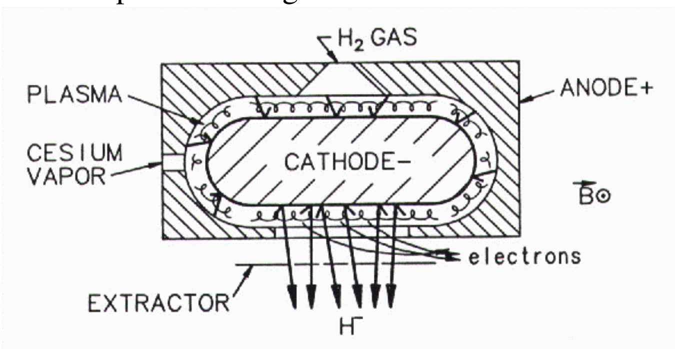
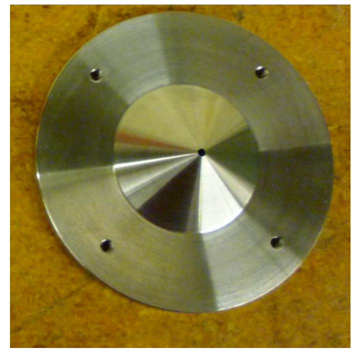
Abstract:

This paper discusses the topics of negative hydrogen ion generation, the mechanics of the HINS ion source, the fundamentals of beam emittance, and the HINS H- source test data.

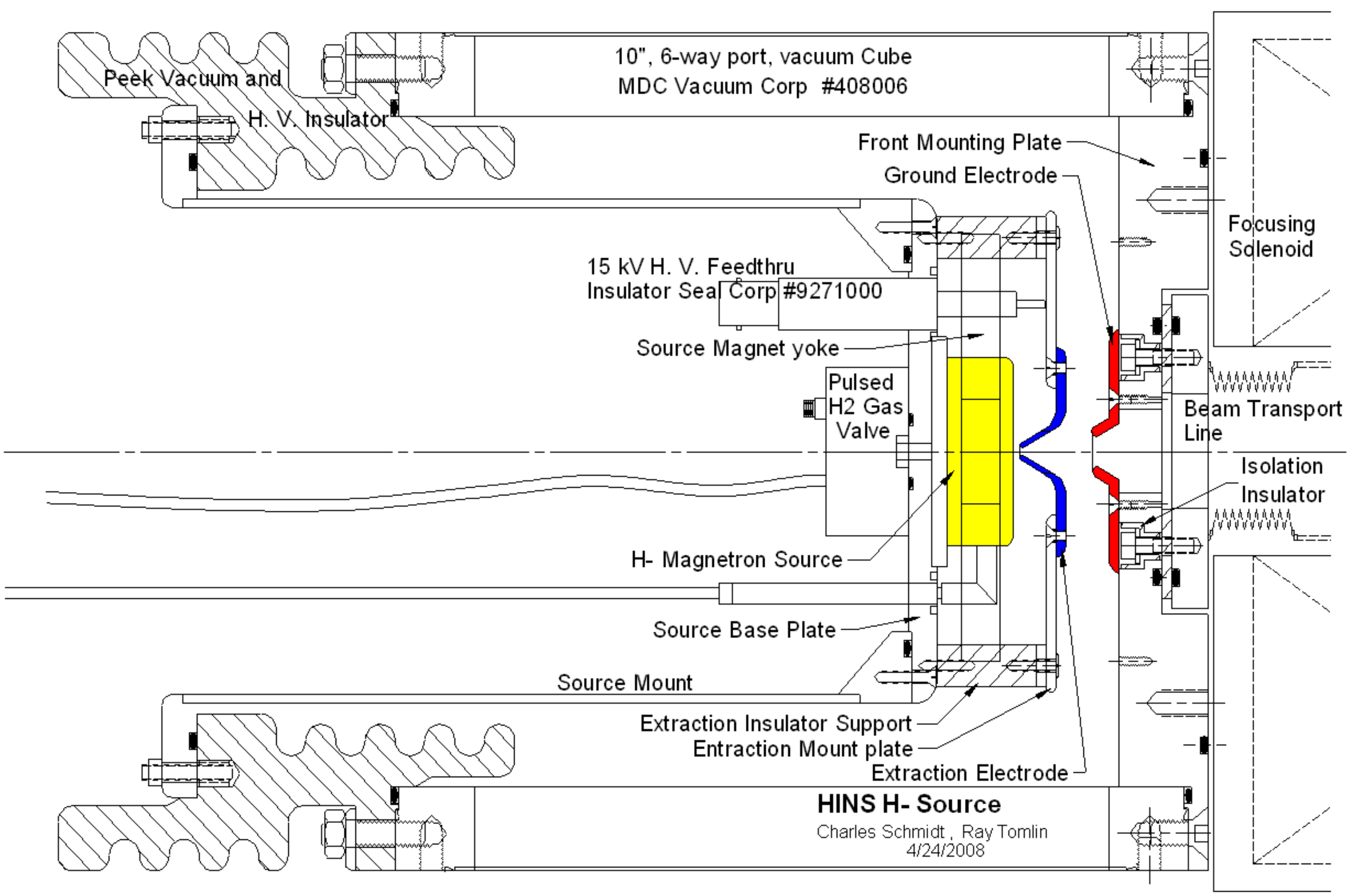
HINS H- Ion Source:

The ion source consists of an oval shaped anode that surrounds a cathode. A gap exists between the anode and cathode. This is where the plasma is created. There are two ports; one for injecting hydrogen gas and one for injecting cesium vapor. A small window is located in the anode wall to allow a path for the hydrogen ions. The plate covering the window collimates the beam into a point source.





The extractor plate cone aperture (figure on the left) is located a small distance away from the point source and has a potential on the order of -30 kilovolts from ground. This attracts and accelerates the H- ions that are pushed away from the source that has a potential of –50k. Once the ions emerge from the extractor plate they are focused electro-statically with an Einzel Lens that is biased at approximately -34kV.



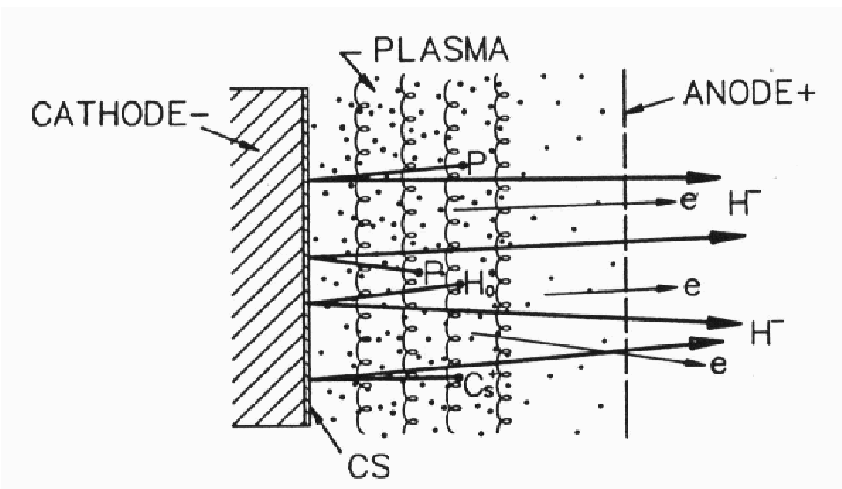
Schematic #1: HINS H- Ion Source
{(Yellow = Anode and Electrode) (Blue = Extraction Plate) (Red = Ground Electrode)}

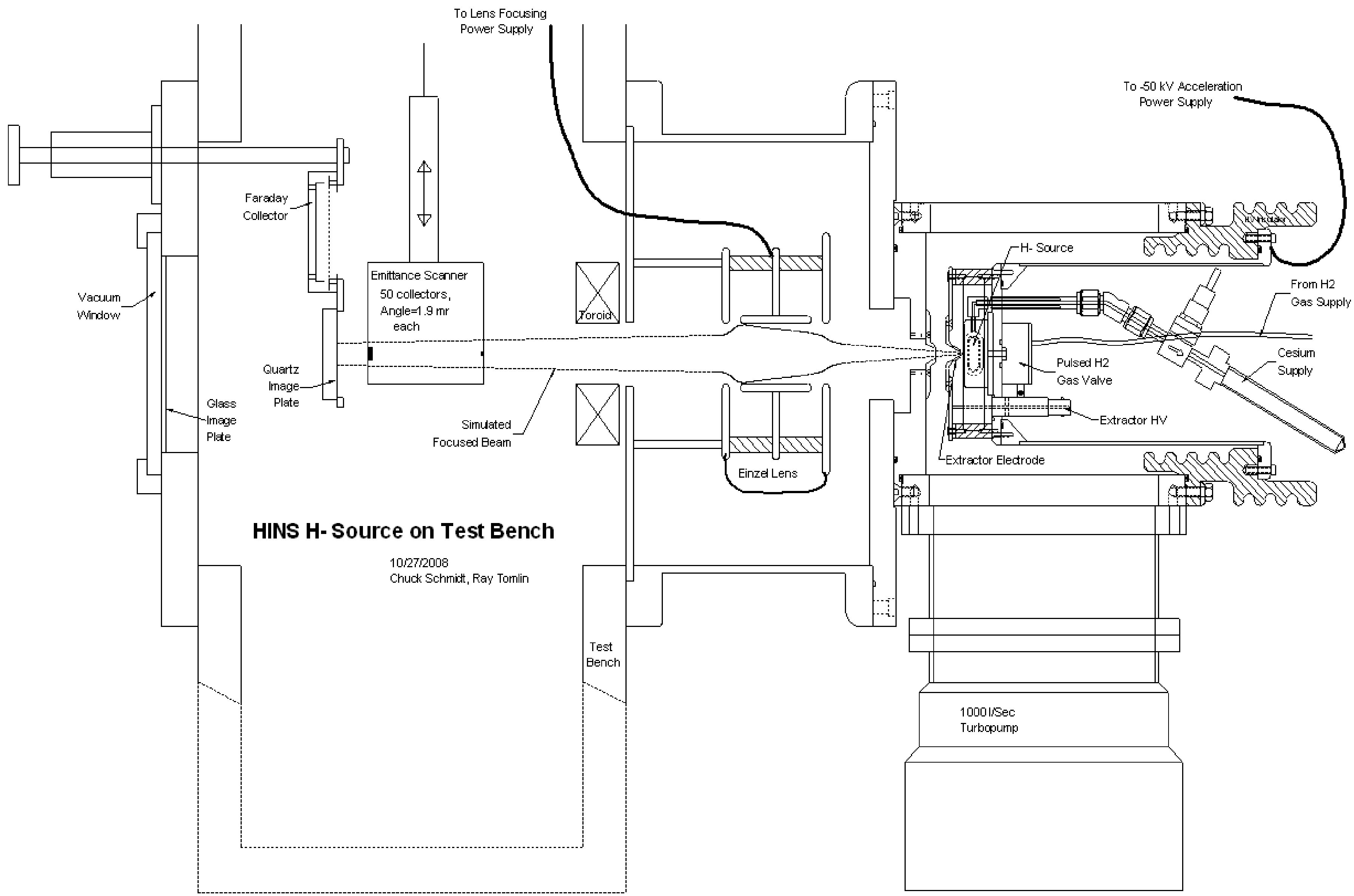
Schematic #1 depicts the anode and cathode in yellow, the extraction plate in blue, and the ground electrode as red. The anode is at –50kV and the cathode is at approximately –50.2kV when pulsed by the arc voltage. This extra 200V starts the electrical arc that causes current to flow between the anode and cathode creating the plasma. The –50kV anode repels the negative hydrogen ions toward the ground electrode while the extraction plate, being at a potential greater than the –50kV source, attracts the negative ions. Generally the extractor plate has a potential of approximately –30kV from ground. This amounts to a 20kV positive attracting potential between the anode and the extraction plate; as experienced by the negative ions.

The second electron in a hydrogen ion has an energy of approximately 0.75eV therefore it is relatively easy to add or remove an electron from it. Because of this, a cathode with a low work function is suited best for making these electrons available. Molybdenum has a work function of 4.0eV to 4.5eV and is used as the cathode material. Cesium has a work function of approximately 1.5eV in the gaseous form, and is injected into the ion generator to lower the work function of the molybdenum to this level. This makes electrons abundantly available for hydrogen atoms and protons to pick up.

Here are some possible variations on how hydrogen ions can be produced in the plasma:

- A positive cesium ion slams into the cathode and ejects a H- ion
- A neutral hydrogen atom slams into the cathode and picks up an electron
- A proton slams into the cathode and picks up 2 electrons
- A proton slams into the cathode and picks up one electron and then picks up another electron in the gap.





To Lens Focusing
Power Supply
To -50 kV Acceleration
Power Supply
Faraday
Collector
Vacuum
Window
Emittance Scanner
50 collectors,
Angle=1.9 mr
each
Toroid
H- Source
From H2
Gas Supply
Cesium
Supply
Pulsed H2
Gas Valve
Extractor HV
Extractor Electrode
Quartz
Image
Plate
Glass
Image
Plate
Simulated
Focused Beam
Einzel Lens
HINS H- Source on Test Bench
10/27/2008
Chuck Schmidt, Ray Tomlin
Test
Bench
1000 l/Sec
Turbopump

Emittance:

Volume emittance is a factor used to describe the quality of a beam of particles. Each particle in a beam has velocity (dx/dt, dy/dt, dz/dt) and location (x,y,z). Volume emittance is defined as a six dimensional hyper-volume:

$$x(dx/dt)y(dy/dt)z(dz/dt) = \int\int\int\int\int\int dx\,dy\,dz\,dp_x\,dp_y\,dp_z$$

where $\int dpx = dx/dt$ and $\int dx = x$

This can be separated into two individual transverse emittances and a longitudinal emittance such that:

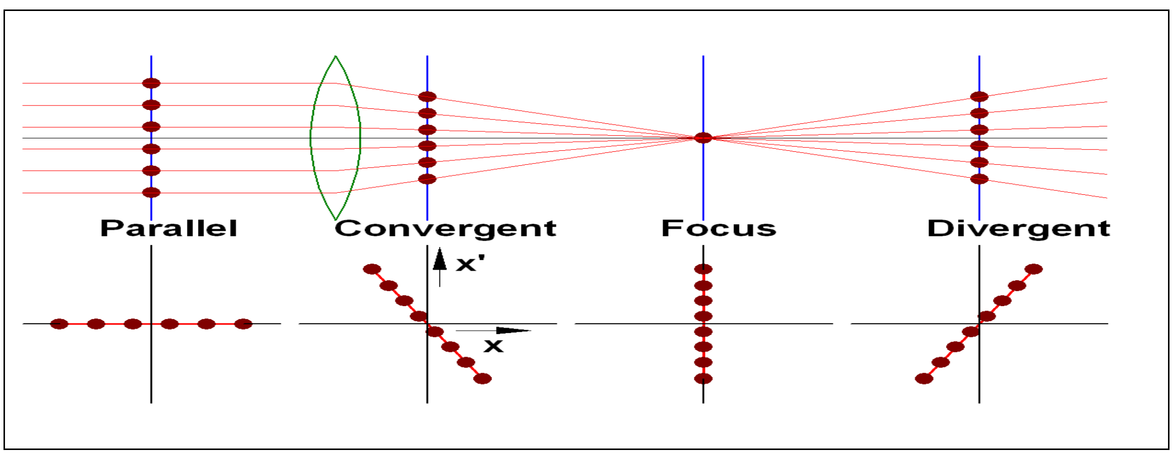
$$x(dx/dt)y(dy/dt)z(dz/dt) = \int\int dx\,dp_x \int\int dy\,dp_y \int\int dz\,dp_z$$

Beam emittances are calculated from $\int\int dx\,dp_x$ and $\int\int dy\,dp_y$ which represent the vertical phase space and horizontal phase space of the beam. The *area* of the beam divided by π, in phase space, is the emittance of the beam:

Horizontal Transverse Emittance = $\varepsilon_h = [\Sigma\ x_i][\Sigma\,(dx/dt)_j]$

Vertical Transverse Emittance = $\varepsilon_v = [\Sigma\ y_i][\Sigma(dy/dt)_j]$

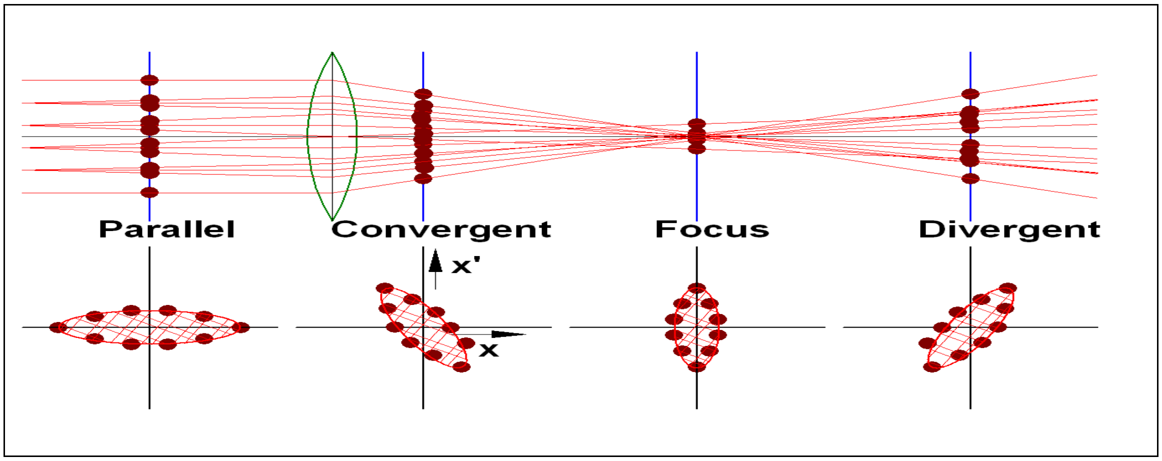
In an ideal beam all of the particles are moving in parallel with the same velocities (dx/dt, dy/dt, dz/dt) therefore, theoretically, the transverse emittance measurements will appear as a straight line along the horizontal coordinate axis.



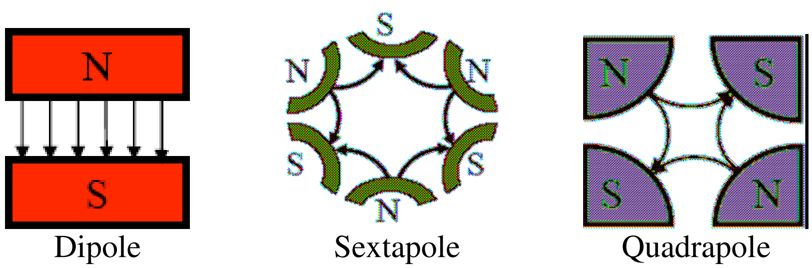
Ideal Lens

Sending the beam through an ideal lens focuses the beam. Particles closer to the edge of the lens are kicked harder than particles near the center. This results in particles further from the center having proportionally more transverse velocity. Particles traveling directly down the beam line are not affected by the lens.

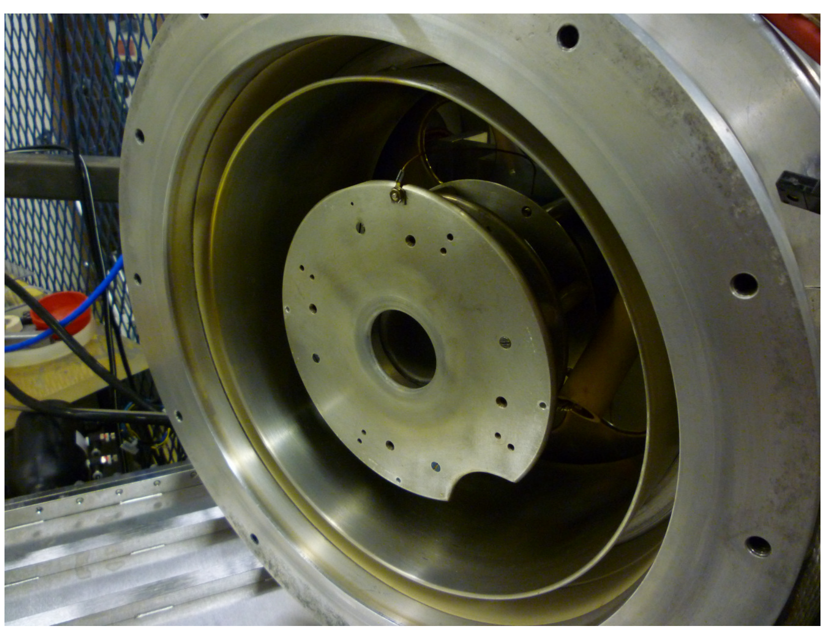
Beam particles are subject to the forces of Thermal Expansion and Space Charge. This is the essence of a non-ideal beam. Thermal Expansion is basically the particles acting as an expanding gas. Space Charge is the effect of the particles in a beam bunch pushing away from each other because the particles have the same charge. These forces cause variations in an individual particles' velocity and location and are managed with various types of focusing magnets, drift spaces, and lenses utilizing electric fields that are placed throughout an accelerator. The end result is an emittance that takes up an *area* divided by π, in phase space.



Non-Ideal Lens

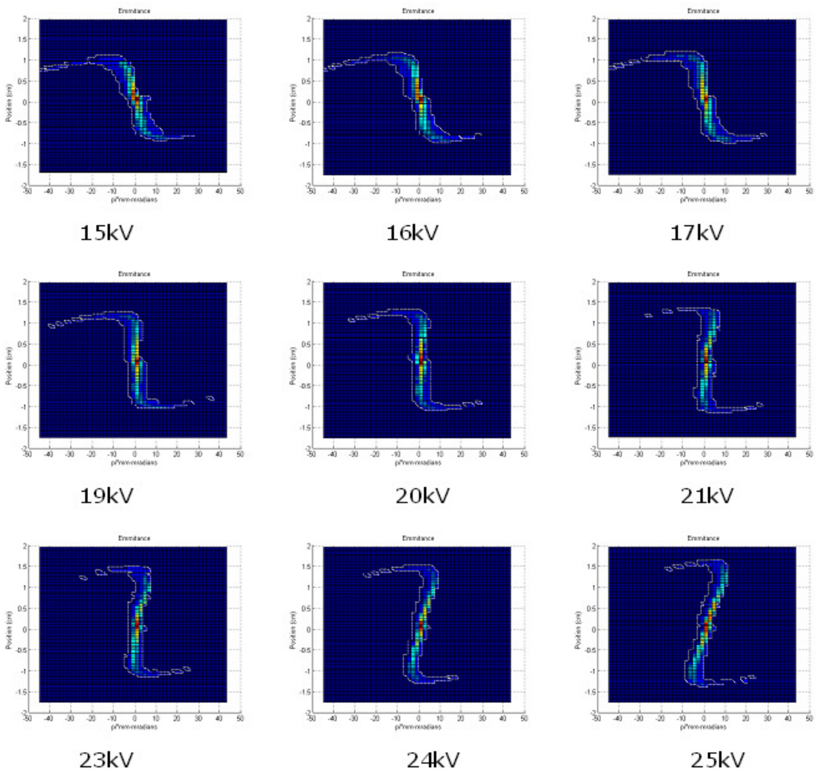


Focusing Magnets



Einzel Focusing Lens (electrostatic)

Below is a series of emittance scans that demonstrate the effects of space charge. Note that as the extraction voltage (the number below each scan) is increased there is a shift in the angle at which the emittance scan is slanted. This effect indicates that the beam starts out converging at 15kV, is focused at 20kV, and ends up diverging at 25kV. As the beam current increases directly with the extraction voltage; there is more space charge pushing the beam apart causing it to diverge. The overall result can be viewed as a twisting of the beam in phase space as shown below.



Normalized Emittance	Extraction Voltage(kV)
0.6588	15
0.6776	16
0.6824	17
0.642	18
0.6542	18
0.6669	19
0.6374	20
0.6828	20
0.5978	21
0.5967	22
0.6083	23
0.58	23
0.597	23
0.5935	24
0.6094	24
0.632	24
0.6677	25
0.7222	25
0.5779	25

Example of space charge effect

4mm-gap, 3mm-hole, ARCSV = 260, Horizontal Emittance Scans

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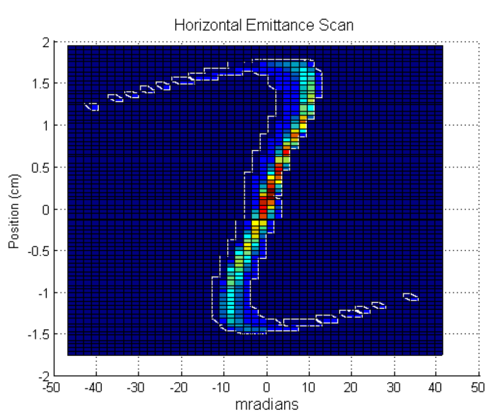
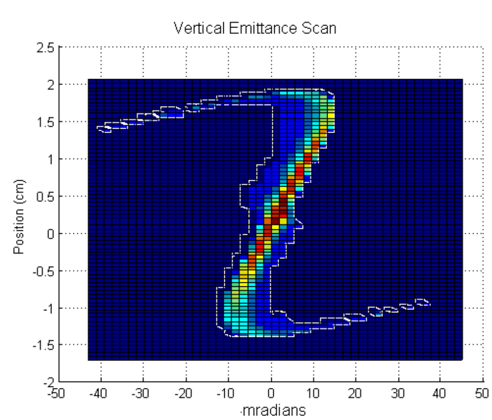
Below are two close up emittance measurements from the HINS hydrogen ion source. Note that the vertical coordinate axis is velocity and the horizontal coordinate axis is the location within the beam. This applies to both figures. From the slant of the graph it can be said that the beam is slightly diverging. The tails indicate that the outer edges of the beam are moving at higher velocity.



Horizontal Scan



Vertical Scan

Transverse emittance is measured by taking a series of measurements as a probe moves across the width or height of the beam. The probe consists of a box with a very fine slit perpendicular to the direction of the scan. A portion of the beam enters the slit and falls onto a stack of metal strips, at the back of the box, that are parallel to the slit.

Note that the beam spreads out inside the box after it enters the slit. Since there are 50 strips in the sensor target, and the distance between each strip from center to center is approximately 6mm, the arc length per strip can be calculated. In this case it is approximately 2.0mradians/strip. The emittance scans above have units of mradians versus the position of the slit in the beam. The specific value of emittance is a measure of the active area on the graph and has the unit of mm-mradians (i.e. $\varepsilon = [\Sigma x_i][\Sigma (dx/dt)_j]$).

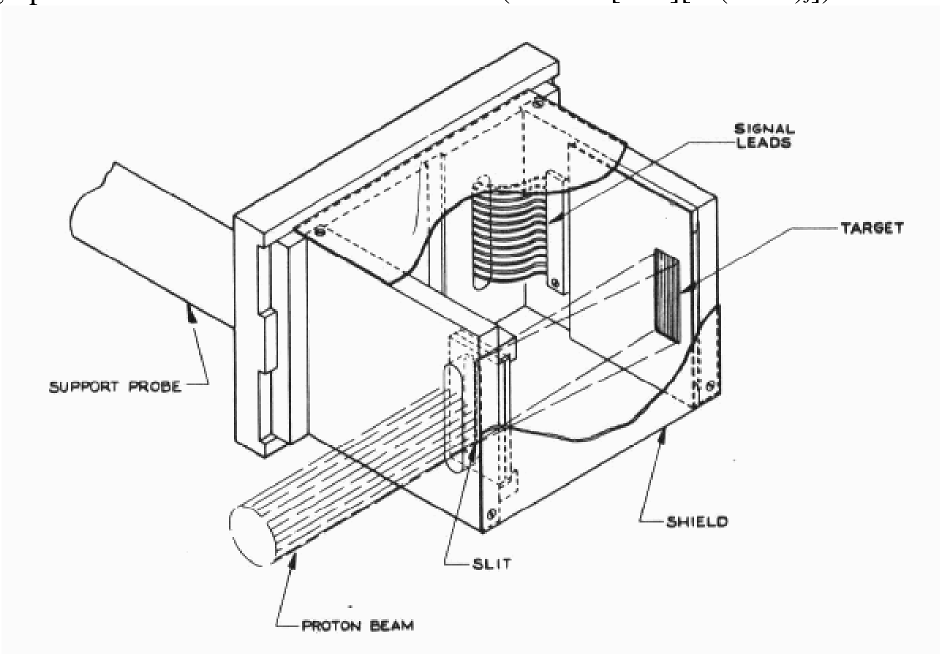
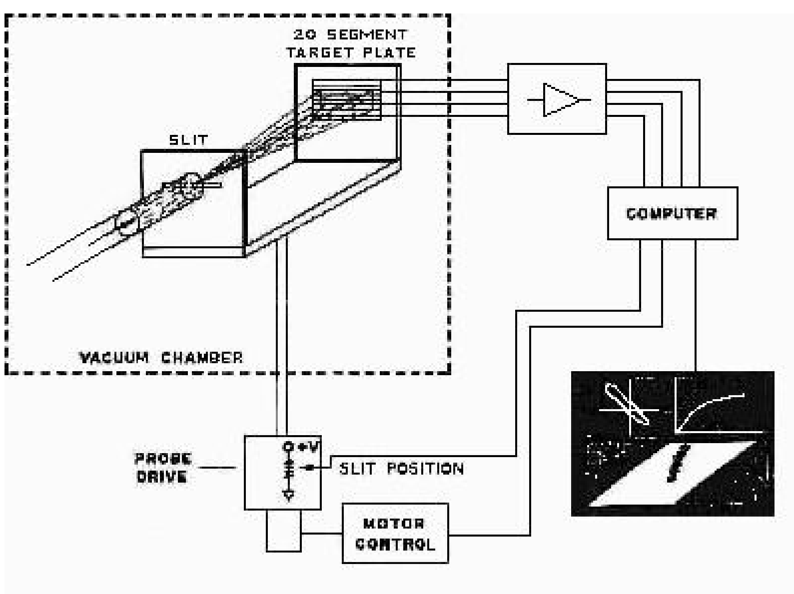


Fig. 2. Destructive emittance probe.

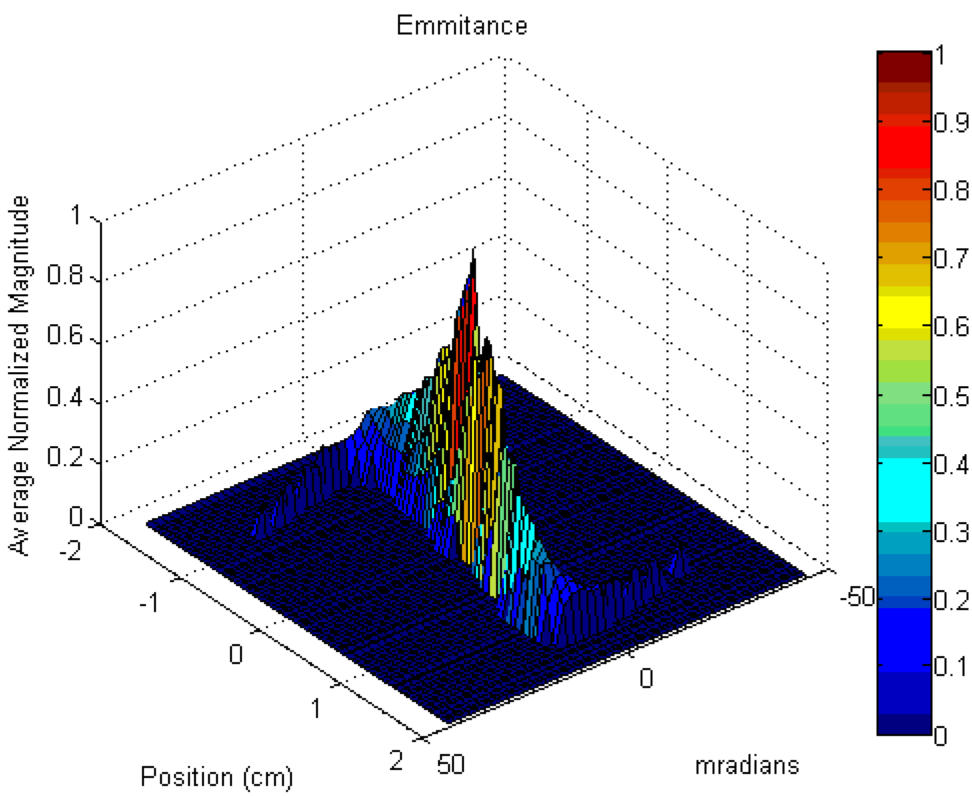
Each metal strip has an induced current due to the beam ions hitting it. Since the ions hitting the strips are of high energy and can cause electrons to eject from the metal; a shield with a window is placed in front of the strips with a grid at positive voltage to attract these electrons. This insures that the currents in the strips are from the ions.



The current in each strip generates a voltage that is routed into an analog to digital converter. These voltages are recorded in matrix form, by the microprocessor, as the probe moves across the beam in steps. The first column of the matrix is the position (i.e. step) of the slit in the beam and the second column is the beam current at that position. An additional 50 columns represent the individual voltages on each of the 50 strips in the probe.

To analyze the data, the matrix is first imported into MatLab where the position column vector and the beam current column vector are separated out from the voltage measurements. The beam current is then averaged and the position vector is set aside for indexing later in the program.

The position and strip voltage data are recorded three samples at a time and is therefore averaged. This results in a smaller matrix with row vectors corresponding to each measurement position and column vectors corresponding to the voltage on each strip. The matrix is then modified and normalized so that values less than 10% are dropped in order to get rid of any noise in the measurements. A surface plot is then made showing the position of the probe slit (i.e. matrix rows) versus the position of each strip (i.e. matrix columns). The value contained in each location of the matrix is the magnitude at that point. This results in a 3-D surface plot. Looking down on this plot from directly above is the transverse emittance scan and can be thought of as looking down onto the data matrix.

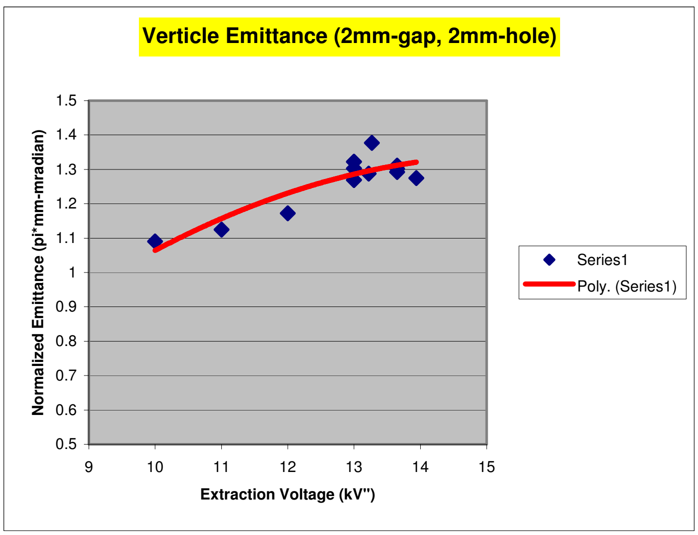


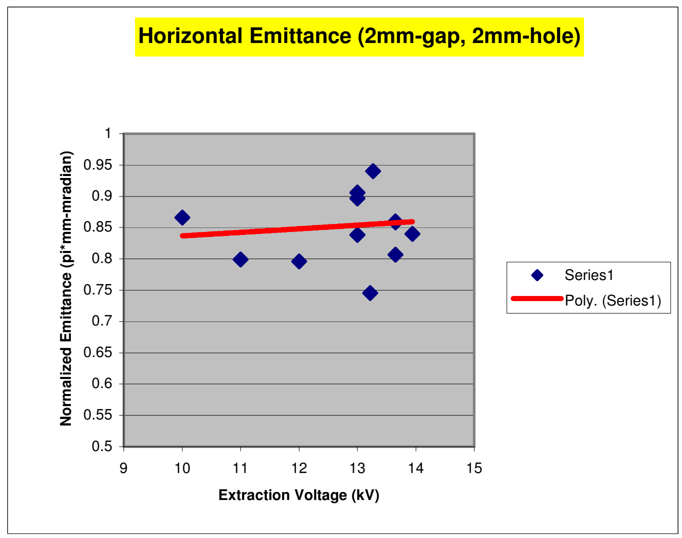
To get the emittance value from the matrix, the area of the *footprint* of the surface must be calculated. First all nonzero values of the matrix are changed to “1” leaving zeros where there is no data. All of the “1”s are added up and multiplied by the area of one square of the matrix. The length the probe transverses divided by the number of steps, which is then multiplied by the length between the strips from center to center, determines the area of one square. For the specific probe used here, the length between strips is 1.87mradians.

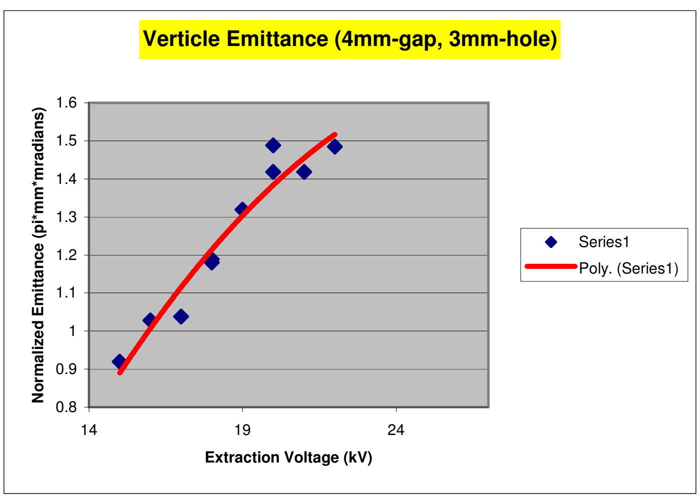
HINS Ion Source Optimization (DATA):

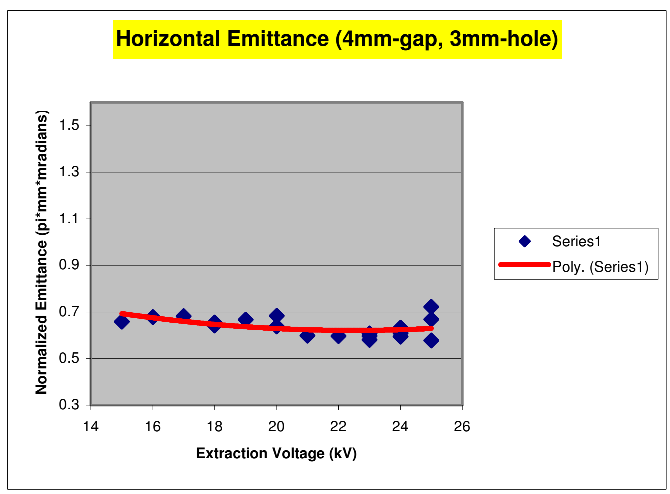
In an effort to optimize the ion source, extraction plate parameters where varied. Measurements where taken over a wide range of extraction voltages, and both horizontal and vertical emittance scans where compared. Overall the horizontal emittance scans where consistently lower in value than the vertical emittance scans. This is most likely due to the direction of the magnetic field around the anode and cathode.

Simulations in SIMION indicated that a larger gap between the anode and extractor plate in addition to a larger hole will perform better at higher extraction voltages. Below are the actual summarized measurements. The horizontal measurements indicate a lower and more stable emittance at a higher extraction voltage. The vertical scans indicate that the emittance increases as the extraction voltage increases; however this rise is probably caused by the presence of the magnetic field.

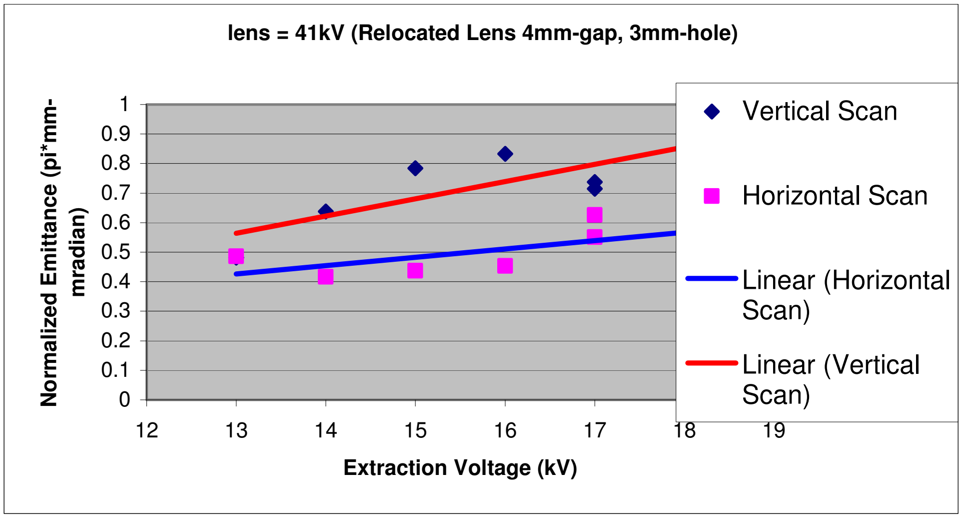




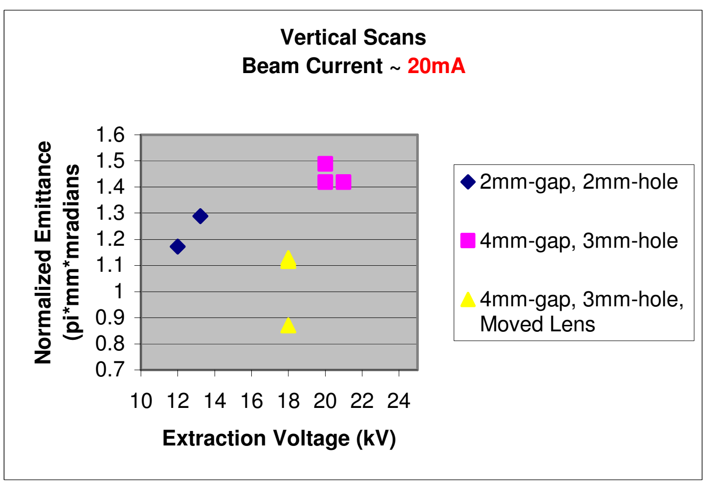


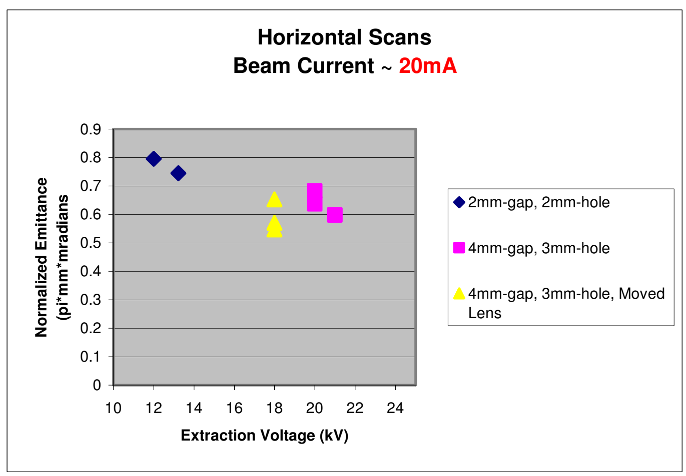


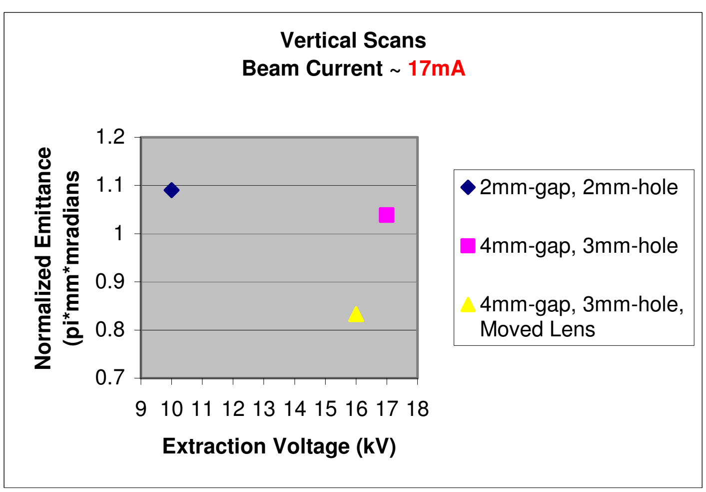
In addition to a larger gap SIMION indicated that moving the lens closer to the ground electrode would increase performance of the ion source. Below is a graph of the data obtained from the configuration with the lens moved closer to the ground electrode by one inch. By comparing the previous graphs with this one it can be seen that this configuration yielded the best overall results for emittance out of the three configurations.

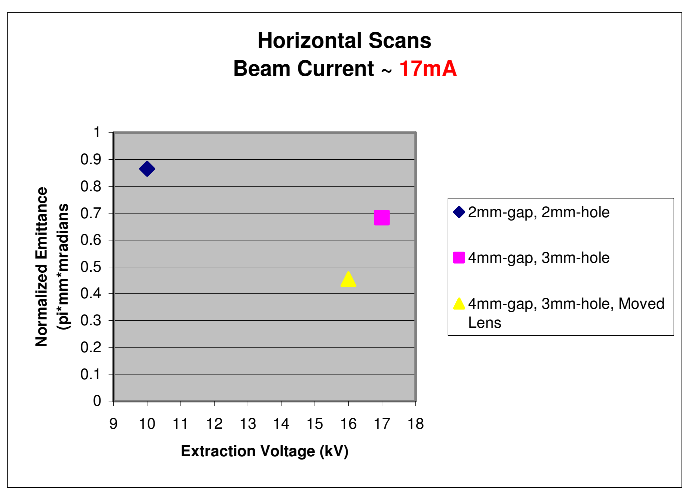


Below are four graphs each of which compares the three tested configurations while operating at the same constant beam current. Note that the configuration with the adjusted lens (yellow triangles) has the lowest emittance values for the given currents.

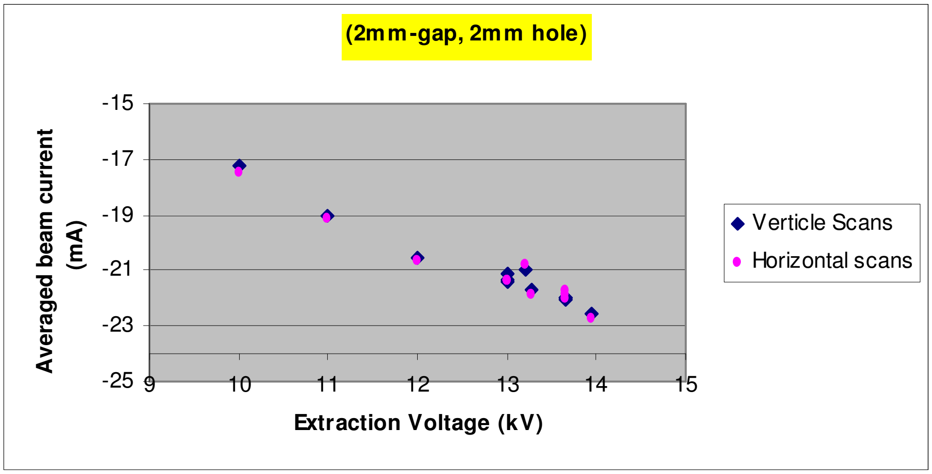


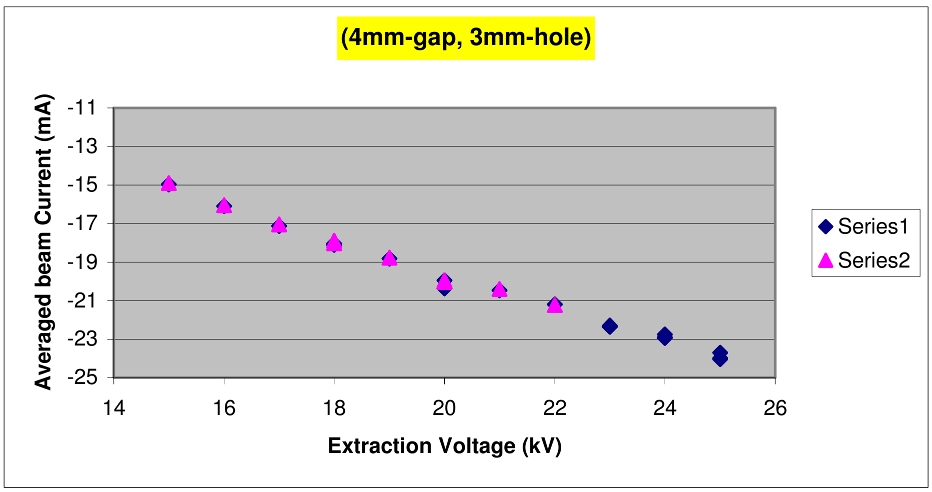


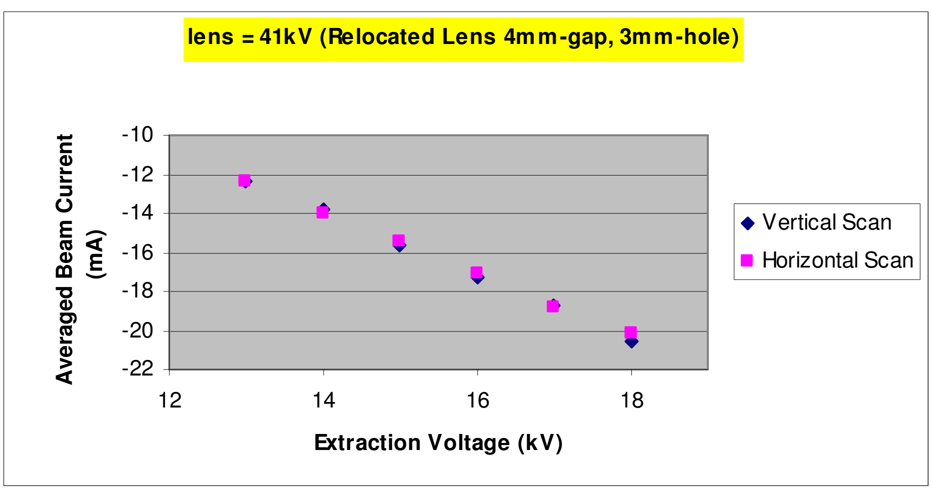




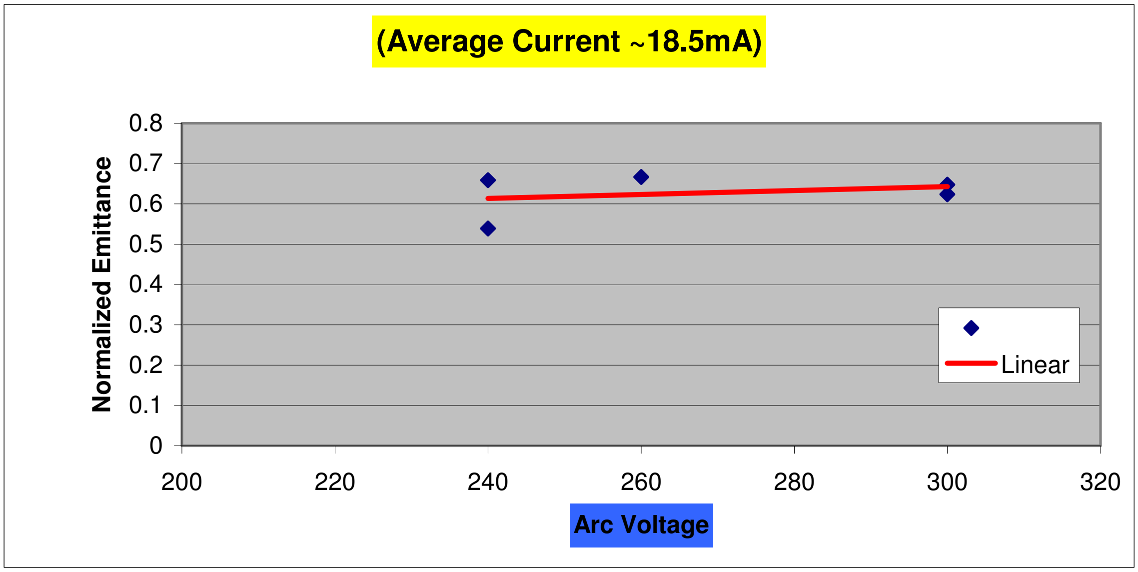
In all three configurations tested, it was found that there is a direct correlation between extraction voltage and beam current. A higher extraction voltage always resulted in a larger beam current. Another interesting trend is that horizontal and vertical scans had approximately the same value of beam current for the same extraction voltage; even though the emittances differed between the two scans.

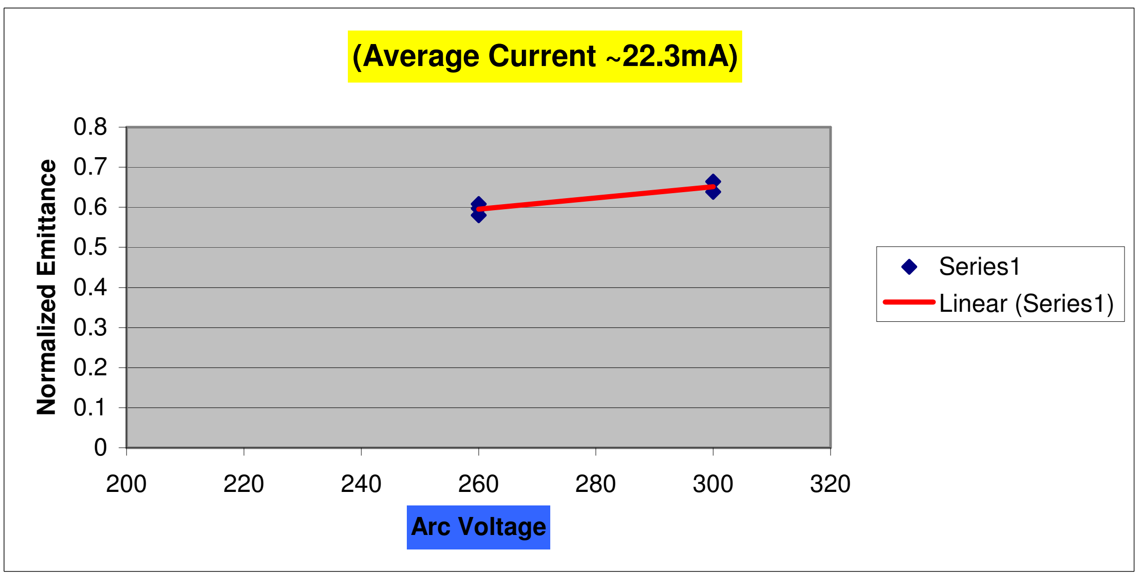






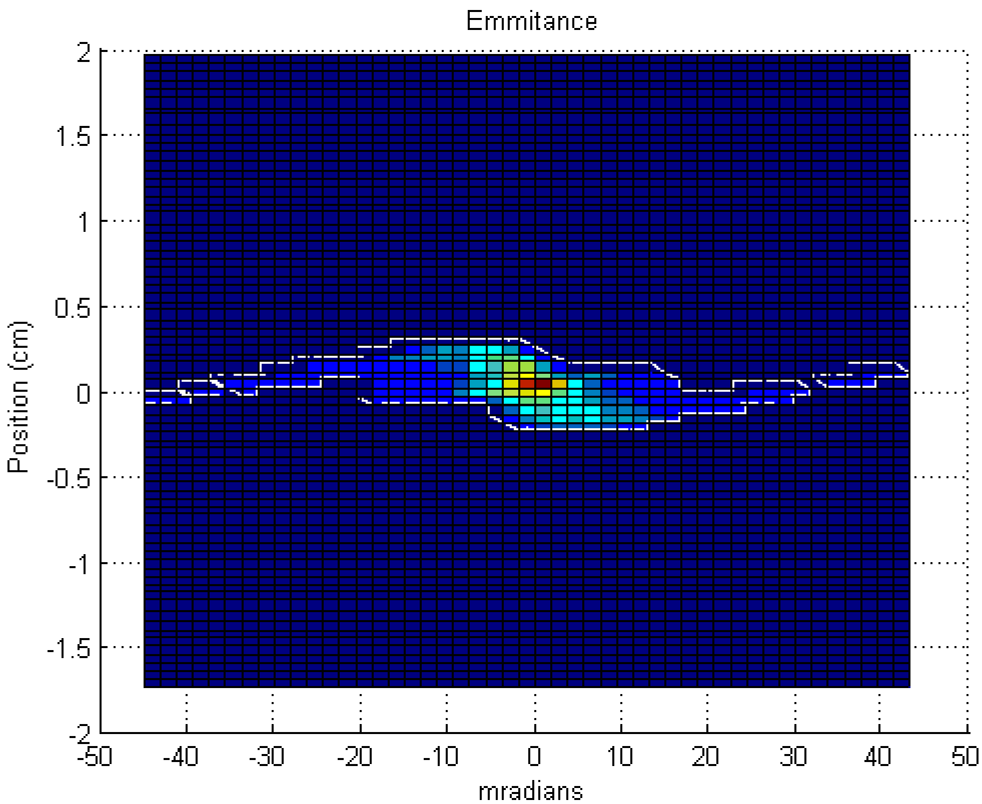
A series of horizontal emittance scans were taken at different arc voltages for a given fixed current. The configuration that produced these scans is the 4mm-gap, 3mm-hole setup before the lens was moved. Below are two graphs showing the scans at 18.5mA and 22.3mA (currents are approximate). Note that the emittance gets slightly larger as the arc-voltage goes up, however this effect is small.





Best Emittance Performance at ~20mA
(Horizontal Scan - Altered Lens Configuration)
Data File: 20090730_HE-18KV_41L.xls

Emittance (pi*mm-mrad)	Normalized Emittance (pi*mm-mrad)	Average Current (mA)	Extraction Voltage (kV)	Lense Voltage (kV)	Cone Spacing (mm)	Cone Angle (deg.)	Apature (mm)
53.1204	0.5471	-20.19	18	41	4	45	3



Conclusions:

•Of the 3 configurations tested, the best design had a 4mm-gap, 3mm-hole, and a lens closer to the ground electrode (1.0 inch space).
•Best emittance was found at a 41kV lens voltage and an 18kV extraction voltage.
•Beam current is directly related to the extraction voltage
•Arc voltage has very little effect on the emittance
•There is a balance to be struck between a lower emittance and a higher extraction voltage (i.e. Beam current)

Acknowledgements:

•Ray Tomlin and Chuck Schmidt (mentors)
•Eugene Evans (Simulations)
•The Lee Teng group and the DOE
•All the people at FermiLab for years of excellent science

```matlab
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%
%This MatLab program calculates beam emittance and normalized emittance%
%                          BetaGamma = .0103                          %
%                Program Author = Doug Frome July 2009                 %
%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%%

%To run this function, Make sure that the ".xls" file is in Microsoft Format
%In other words, import data into Microsoft Excel and then "save as"

function importfile(fileToRead1);
newData1 = xlsread(fileToRead1);

A = newData1; %used for averaging the values in the newData1 matrix

[RowNum,ColNum] = size(A)

%-----------------------------------------------------------------------------------------
Rows = round((RowNum)/4) %Round off the number of rows and divide by 4
                         %The 4 represents 3 samples plus one blank space
                         %(i.e The form in which the data is given from the
                         %file)
AverageVector = zeros(Rows,ColNum);%Create a matrix the size of the data file

for r = 1:1:Rows  %cycle from 1st row to last row

    AverageVector (r,:) = (A(4*r-3,:) + A(4*r-2,:) + A(4*r-1,:))/3;
    %This averages the values...it adds each of the values contained in 3
    %rows together and then divides by 3.  The end product is a matrix with
    %averaged data rows each separated by 3 rows of zeros
end

position = AverageVector(:,1); %position is the 1st column
toroidcurrent = AverageVector(:,2); %toroid current is the 2nd column
AverageCurrent = (sum(toroidcurrent))/(length(toroidcurrent))
%Individual Wire data is on the remaining 48 columns

DataVector = AverageVector(:,3:end);%This takes the 48 columns of data

normal = max(max(DataVector)); %Find the max value, column and row
NormalizedMatrix = DataVector/normal; %Divide all data by the largest value(normal)
NormalizedMatrix = (NormalizedMatrix > (.1)).*NormalizedMatrix; %Take off ten percent
from each value

EmittanceMatrix = NormalizedMatrix > (0); %This make a matrix of ones and zeros
Emittance = sum(sum(EmittanceMatrix))*1.87*10*(abs(position(1)-
position(end)))/(length(position)*pi)
NormalizedEmittance = Emittance*.0103
%-----------------------------------------------------------------------------------------
MaxMatrix = NormalizedMatrix >= 1;
[i,j] = find(MaxMatrix);%Find the Max value indicies of the position vector

a = 0;
for index = j:1:48;

       VectorX(index)= 0 + a;
       a = a + 1.87;
end
a = 0;
for index = j:-1:1;

       VectorX(index)= 0 + a;
       a = a - 1.87;
end
%-----------------------------------------------------------------------------------------
[i,j] = min(position');%Find the Min value indicies of the position vector
a = j;
for index = j:1:length(position');

       VectorY(index)= position(a)';
       a = a + 1;

end
a = j;
for index = j:-1:1;

       VectorY(index)= position(a)';
       a = a - 1;;
end                                                              (continued)…
```

```
%-------------------------------------------------------------------------------------
figure(1)
surf(VectorX, VectorY,NormalizedMatrix); %Plot the swept data on a surface

xlabel('pi*mm-mradians');  %Label and title graph
ylabel('Position (cm)');
zlabel('Average Normalized Magnitude')
title('Emittance');

figure(2)
surf(VectorX, VectorY,DataVector); %Plot the swept data on a surface
xlabel('pi*mm-mradians');  %Label and title graph
ylabel('Position (cm)');
zlabel('Average NON-Normalized Magnitude')
title('Emittance');

figure(3)

plot( position,toroidcurrent);
xlabel('Position (cm)');
ylabel('Beam Current (mA)');

figure(4)
surf(VectorX, VectorY,EmittanceMatrix*2);
```